# COMPUTER GRAPHICS

## C VERSION

DONALD HEARN ▪ M. PAULINE BAKER

SECOND EDITION

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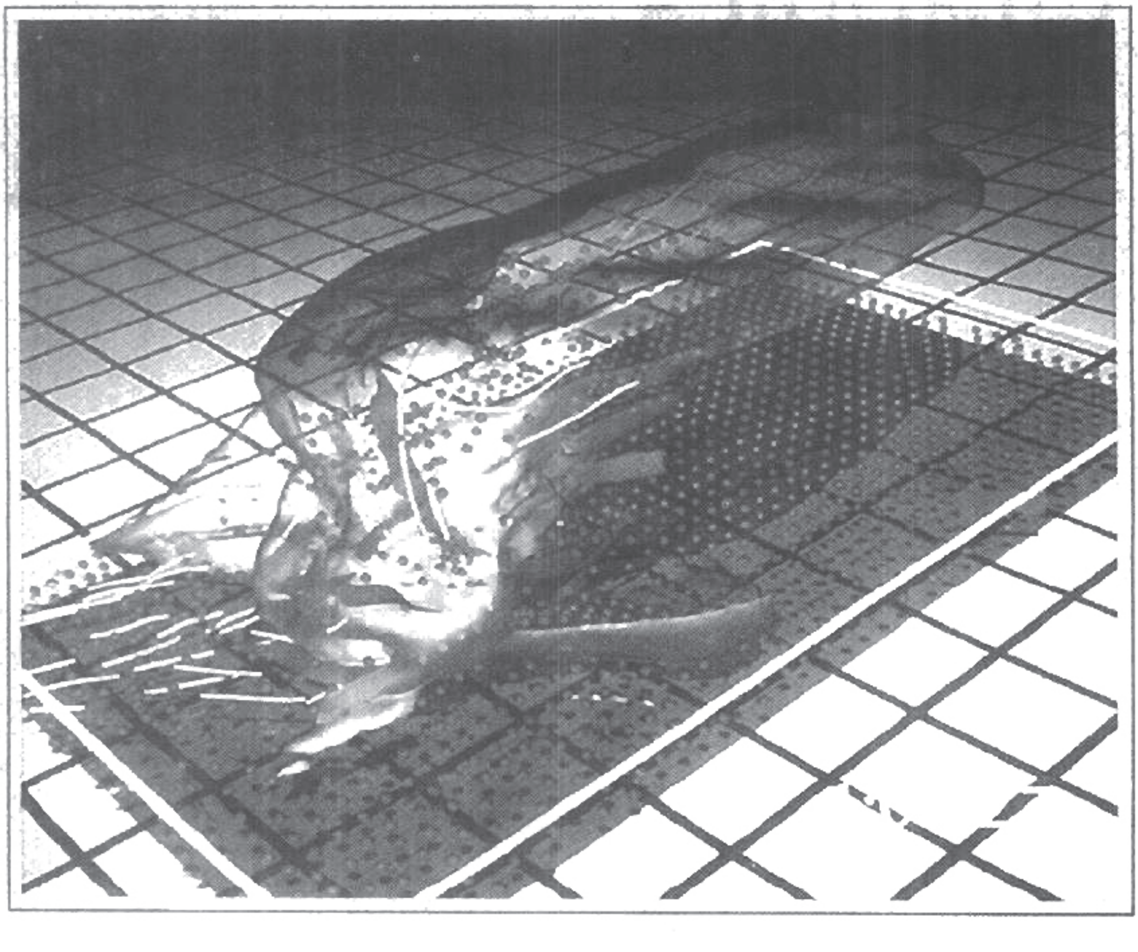
# Computer Graphics
## C Version

CHAPTER

# 1 A Survey of Computer Graphics



Computers have become a powerful tool for the rapid and economical production of pictures. There is virtually no area in which graphical displays cannot be used to some advantage, and so it is not surprising to find the use of computer graphics so widespread. Although early applications in engineering and science had to rely on expensive and cumbersome equipment, advances in computer technology have made interactive computer graphics a practical tool. Today, we find computer graphics used routinely in such diverse areas as science, engineering, medicine, business, industry, government, art, entertainment, advertising, education, and training. Figure 1-1 summarizes the many applications of graphics in simulations, education, and graph presentations. Before we get into the details of how to do computer graphics, we first take a short tour through a gallery of graphics applications.

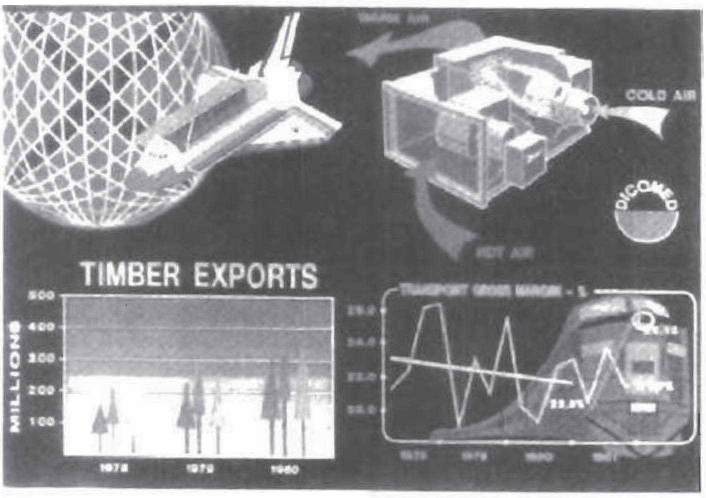



*Figure 1-1*
Examples of computer graphics applications. (*Courtesy of DICOMED Corporation.*)

## 1-1 COMPUTER-AIDED DESIGN

A major use of computer graphics is in design processes, particularly for engineering and architectural systems, but almost all products are now computer designed. Generally referred to as **CAD, computer-aided design** methods are now routinely used in the design of buildings, automobiles, aircraft, watercraft, spacecraft, computers, textiles, and many, many other products.

For some design applications, objects are first displayed in a wireframe outline form that shows the overall shape and internal features of objects. Wireframe displays also allow designers to quickly see the effects of interactive adjustments to design shapes. Figures 1-2 and 1-3 give examples of wireframe displays in design applications.

Software packages for CAD applications typically provide the designer with a multi-window environment, as in Figs. 1-4 and 1-5. The various displayed windows can show enlarged sections or different views of objects.

Circuits such as the one shown in Fig. 1-5 and networks for communications, water supply, or other utilities are constructed with repeated placement of a few graphical shapes. The shapes used in a design represent the different network or circuit components. Standard shapes for electrical, electronic, and logic circuits are often supplied by the design package. For other applications, a designer can create personalized symbols that are to be used to construct the network or circuit. The system is then designed by successively placing components into the layout, with the graphics package automatically providing the connections between components. This allows the designer to quickly try out alternate circuit schematics for minimizing the number of components or the space required for the system.

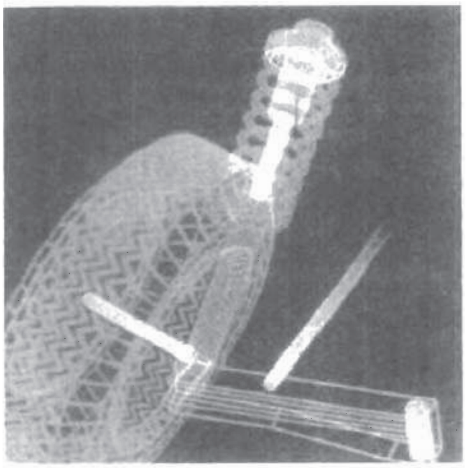
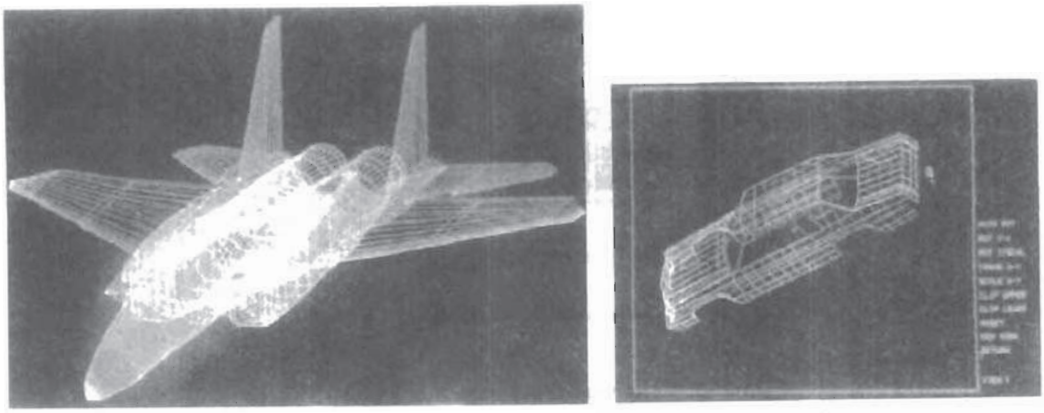


*Figure 1-2*
Color-coded wireframe display for an automobile wheel assembly.
*(Courtesy of Evans & Sutherland.)*



(a) (b)

*Figure 1-3*
Color-coded wireframe displays of body designs for an aircraft and an automobile. (*Courtesy of (a) Evans & Sutherland and (b) Megatek Corporation.*)

Animations are often used in CAD applications. Real-time animations using wireframe displays on a video monitor are useful for testing performance of a vehicle or system, as demonstrated in Fig. 1-6. When we do not display objects with rendered surfaces, the calculations for each segment of the animation can be performed quickly to produce a smooth real-time motion on the screen. Also, wireframe displays allow the designer to see into the interior of the vehicle and to watch the behavior of inner components during motion. Animations in *virtual-reality* environments are used to determine how vehicle operators are affected by

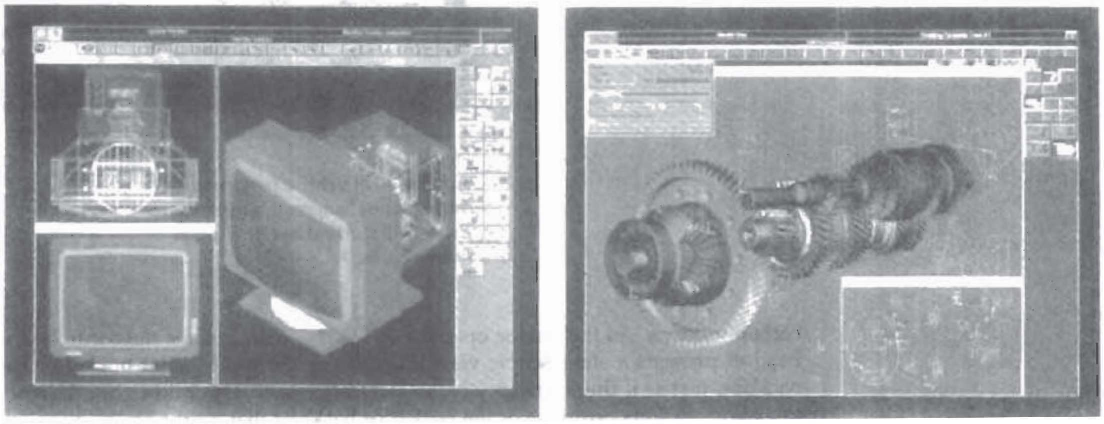


*Figure 1-4*
Multiple-window, color-coded CAD workstation displays. (*Courtesy of Intergraph Corporation.*)

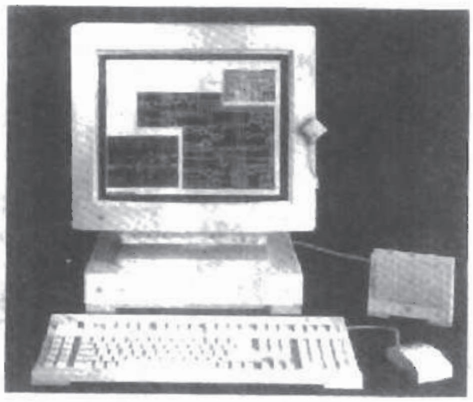


*Figure 1-5*
A circuit-design application, using multiple windows and color-coded logic components, displayed on a Sun workstation with attached speaker and microphone. (*Courtesy of Sun Microsystems.*)

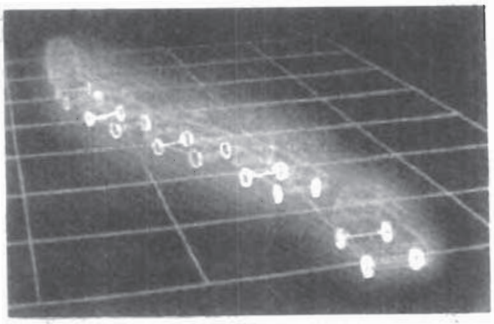


*Figure 1-6*
Simulation of vehicle performance during lane changes. (*Courtesy of Evans & Sutherland and Mechanical Dynamics, Inc.*)

certain motions. As the tractor operator in Fig. 1-7 manipulates the controls, the headset presents a stereoscopic view (Fig. 1-8) of the front-loader bucket or the backhoe, just as if the operator were in the tractor seat. This allows the designer to explore various positions of the bucket or backhoe that might obstruct the operator's view, which can then be taken into account in the overall tractor design. Figure 1-9 shows a composite, wide-angle view from the tractor seat, displayed on a standard video monitor instead of in a virtual three-dimensional scene. And Fig. 1-10 shows a view of the tractor that can be displayed in a separate window or on another monitor.


*Figure 1-7*
Operating a tractor in a virtual-reality environment. As the controls are moved, the operator views the front loader, backhoe, and surroundings through the headset. *(Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, and Caterpillar, Inc.)*

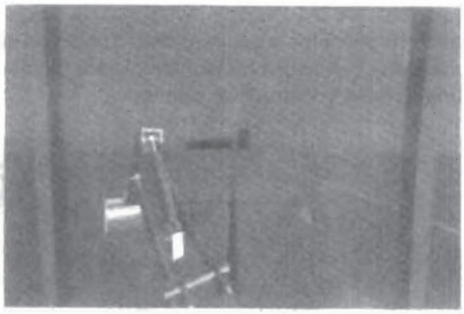


*Figure 1-8*
A headset view of the backhoe presented to the tractor operator. *(Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, and Caterpillar, Inc.)*

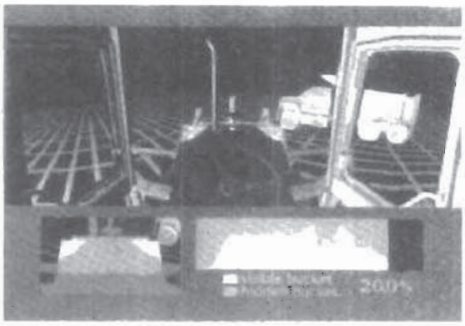


*Figure 1-9*
Operator's view of the tractor bucket, composited in several sections to form a wide-angle view on a standard monitor. *(Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, and Caterpillar, Inc.)*

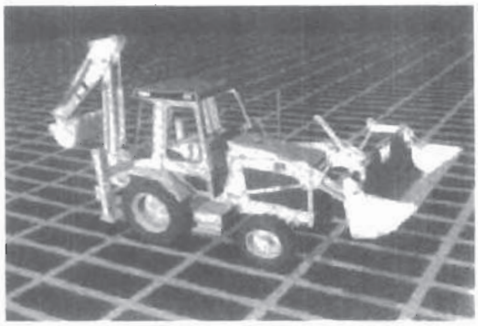
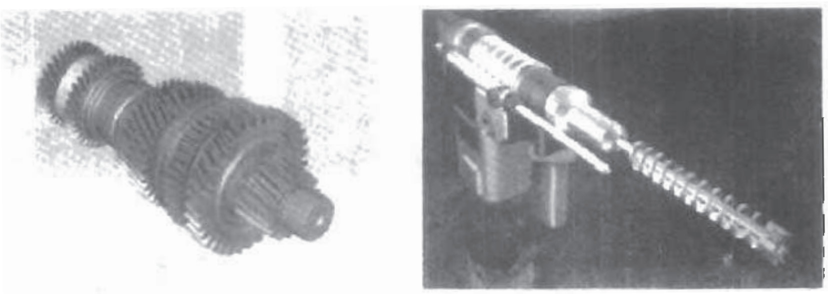


*Figure 1-10*
View of the tractor displayed on a standard monitor. (*Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, and Caterpillar, Inc.*)

When object designs are complete, or nearly complete, realistic lighting models and surface rendering are applied to produce displays that will show the appearance of the final product. Examples of this are given in Fig. 1-11. Realistic displays are also generated for advertising of automobiles and other vehicles using special lighting effects and background scenes (Fig. 1-12).

The manufacturing process is also tied in to the computer description of designed objects to automate the construction of the product. A circuit board layout, for example, can be transformed into a description of the individual processes needed to construct the layout. Some mechanical parts are manufactured by describing how the surfaces are to be formed with machine tools. Figure 1-13 shows the path to be taken by machine tools over the surfaces of an object during its construction. Numerically controlled machine tools are then set up to manufacture the part according to these construction layouts.



(a) (b)

*Figure 1-11*
Realistic renderings of design products. (*Courtesy of (a) Intergraph Corporation and (b) Evans & Sutherland.*)

Figure 1-12
Studio lighting effects and realistic surface-rendering techniques are applied to produce advertising pieces for finished products. The data for this rendering of a Chrysler Laser was supplied by Chrysler Corporation. (*Courtesy of Eric Haines, 3D/EYE Inc.*)

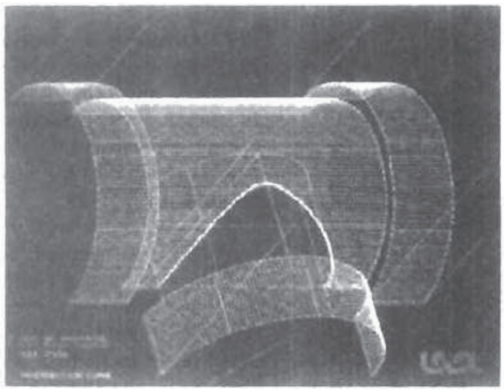


*Figure 1-13*
A CAD layout for describing the numerically controlled machining of a part. The part surface is displayed in one color and the tool path in another color. (*Courtesy of Los Alamos National Laboratory.*)

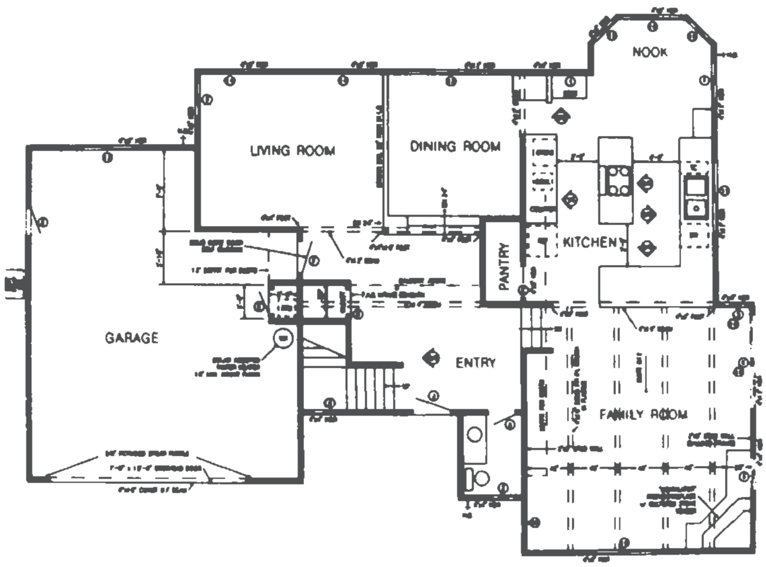



*Figure 1-14*
Architectural CAD layout for a building design. (*Courtesy of Precision Visuals, Inc., Boulder, Colorado.*)

Architects use interactive graphics methods to lay out floor plans, such as Fig. 1-14, that show the positioning of rooms, doors, windows, stairs, shelves, counters, and other building features. Working from the display of a building layout on a video monitor, an electrical designer can try out arrangements for wiring, electrical outlets, and fire warning systems. Also, facility-layout packages can be applied to the layout to determine space utilization in an office or on a manufacturing floor.

Realistic displays of architectural designs, as in Fig. 1-15, permit both architects and their clients to study the appearance of a single building or a group of buildings, such as a campus or industrial complex. With virtual-reality systems, designers can even go for a simulated "walk" through the rooms or around the outsides of buildings to better appreciate the overall effect of a particular design. In addition to realistic exterior building displays, architectural CAD packages also provide facilities for experimenting with three-dimensional interior layouts and lighting (Fig. 1-16).

Many other kinds of systems and products are designed using either general CAD packages or specially developed CAD software. Figure 1-17, for example, shows a rug pattern designed with a CAD system.

(a)

(b)

*Figure 1-15*
Realistic, three-dimensional renderings of building designs. (a) A street-level perspective for the World Trade Center project. (*Courtesy of Skidmore, Owings & Merrill.*)
(b) Architectural visualization of an atrium, created for a computer animation by Marialine Prieur, Lyon, France. (*Courtesy of Thomson Digital Image, Inc.*)

*Figure 1-16*
A hotel corridor providing a sense of movement by placing light fixtures along an undulating path and creating a sense of entry by using light towers at each hotel room. (*Courtesy of Skidmore, Owings & Merrill.*)

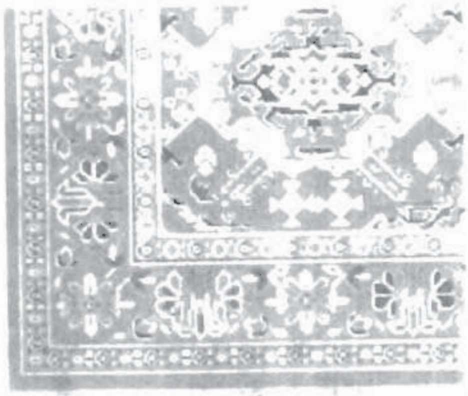


*Figure 1-17*
Oriental rug pattern created with computer graphics design methods. (*Courtesy of Lexidata Corporation.*)

## 1-2 PRESENTATION GRAPHICS

Another major application area is **presentation graphics**, used to produce illustrations for reports or to generate 35-mm slides or transparencies for use with projectors. Presentation graphics is commonly used to summarize financial, statistical, mathematical, scientific, and economic data for research reports, managerial reports, consumer information bulletins, and other types of reports. Workstation devices and service bureaus exist for converting screen displays into 35-mm slides or overhead transparencies for use in presentations. Typical examples of presentation graphics are bar charts, line graphs, surface graphs, pie charts, and other displays showing relationships between multiple parameters.

Figure 1-18 gives examples of two-dimensional graphics combined with geographical information. This illustration shows three color-coded bar charts combined onto one graph and a pie chart with three sections. Similar graphs and charts can be displayed in three dimensions to provide additional information. Three-dimensional graphs are sometimes used simply for effect; they can provide a more dramatic or more attractive presentation of data relationships. The charts in Fig. 1-19 include a three-dimensional bar graph and an exploded pie chart.

Additional examples of three-dimensional graphs are shown in Figs. 1-20 and 1-21. Figure 1-20 shows one kind of surface plot, and Fig. 1-21 shows a two-dimensional contour plot with a height surface.

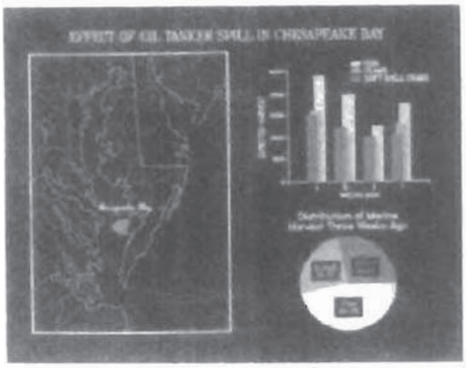


*Figure 1-18*
Two-dimensional bar chart and pie chart linked to a geographical chart. (*Courtesy of Computer Associates, copyright © 1992. All rights reserved.*)

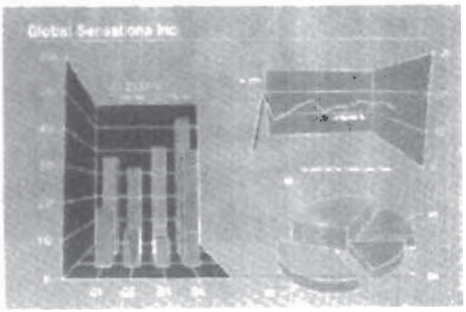


*Figure 1-19*
Three-dimensional bar chart, exploded pie chart, and line graph. (*Courtesy of Computer Associates, copyright © 1992. All rights reserved.*)

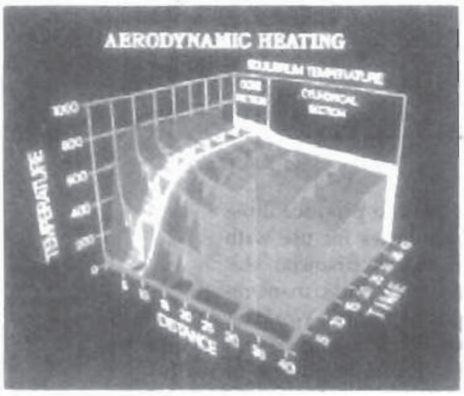



*Figure 1-20*
Showing relationships with a surface chart. (*Courtesy of Computer Associates, copyright © 1992. All rights reserved.*)

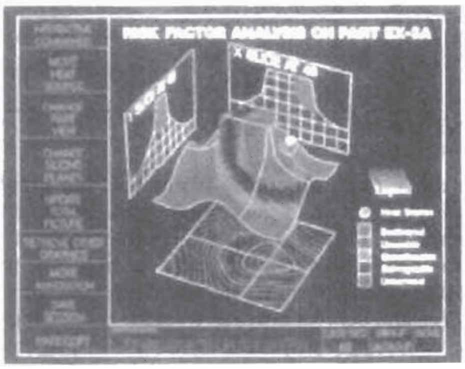


*Figure 1-21*
Plotting two-dimensional contours in the ground plane, with a height field plotted as a surface above the ground plane. (*Courtesy of Computer Associates, copyright © 1992. All rights reserved.*)

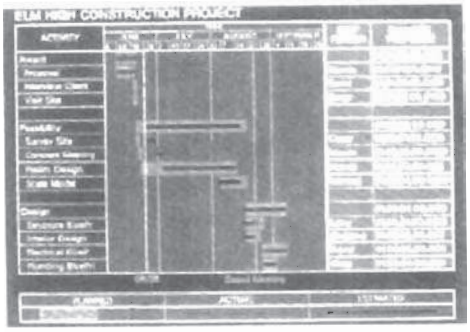


*Figure 1-22*
Time chart displaying relevant information about project tasks. (*Courtesy of Computer Associates, copyright © 1992. All rights reserved.*)

Figure 1-22 illustrates a time chart used in task planning. Time charts and task network layouts are used in project management to schedule and monitor the progress of projects.

## 1-3 COMPUTER ART

Computer graphics methods are widely used in both fine art and commercial art applications. Artists use a variety of computer methods, including special-purpose hardware, artist's paintbrush programs (such as Lumena), other paint packages (such as PixelPaint and SuperPaint), specially developed software, symbolic mathematics packages (such as Mathematica), CAD packages, desktop publishing software, and animation packages that provide facilities for designing object shapes and specifiying object motions.

Figure 1-23 illustrates the basic idea behind a *paintbrush* program that allows artists to "paint" pictures on the screen of a video monitor. Actually, the picture is usually painted electronically on a graphics tablet (digitizer) using a stylus, which can simulate different brush strokes, brush widths, and colors. A paintbrush program was used to create the characters in Fig. 1-24, who seem to be busy on a creation of their own.

A paintbrush system, with a Wacom cordless, pressure-sensitive stylus, was used to produce the electronic painting in Fig. 1-25 that simulates the brush strokes of Van Gogh. The stylus translates changing hand pressure into variable line widths, brush sizes, and color gradations. Figure 1-26 shows a watercolor painting produced with this stylus and with software that allows the artist to create watercolor, pastel, or oil brush effects that simulate different drying out times, wetness, and footprint. Figure 1-27 gives an example of paintbrush methods combined with scanned images.

Fine artists use a variety of other computer technologies to produce images. To create pictures such as the one shown in Fig. 1-28, the artist uses a combination of three-dimensional modeling packages, texture mapping, drawing programs, and CAD software. In Fig. 1-29, we have a painting produced on a pen

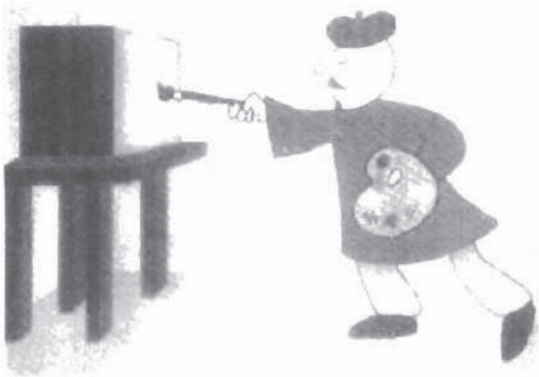


*Figure 1-23*
Cartoon drawing produced with a paintbrush program, symbolically illustrating an artist at work on a video monitor. (*Courtesy of Gould Inc., Imaging & Graphics Division and Aurora Imaging.*)

plotter with specially designed software that can create "automatic art" without intervention from the artist.

Figure 1-30 shows an example of "mathematical" art. This artist uses a combination of mathematical functions, fractal procedures, Mathematica software, ink-jet printers, and other systems to create a variety of three-dimensional and two-dimensional shapes and stereoscopic image pairs. Another example of elec-

*Figure 1-24*
Cartoon demonstrations of an "artist" creating a picture with a paintbrush system. The picture, drawn on a graphics tablet, is displayed on the video monitor as the elves look on. In (b), the cartoon is superimposed on the famous Thomas Nast drawing of Saint Nicholas, which was input to the system with a video camera, then scaled and positioned. (*Courtesy Gould Inc., Imaging & Graphics Division and Aurora Imaging.*)

*Figure 1-25*
A Van Gogh look-alike created by graphics artist Elizabeth O'Rourke with a cordless, pressure-sensitive stylus. (*Courtesy of Wacom Technology Corporation.*)

*Figure 1-26*
An electronic watercolor, painted by John Derry of Time Arts, Inc. using a cordless, pressure-sensitive stylus and Lumena gouache-brush software. (*Courtesy of Wacom Technology Corporation.*)

*Figure 1-27*
The artist of this picture, called *Electronic Avalanche*, makes a statement about our entanglement with technology using a personal computer with a graphics tablet and Lumena software to combine renderings of leaves, flower petals, and electronics components with scanned images. (*Courtesy of the Williams Gallery. Copyright © 1991 by Joan Truckenbrod, The School of the Art Institute of Chicago.*)

*Figure 1-28*
From a series called *Spheres of Influence*, this electronic painting (entitled, *Whigmalaree*) was created with a combination of methods using a graphics tablet, three-dimensional modeling, texture mapping, and a series of transformations. (*Courtesy of the Williams Gallery. Copyright © 1992 by Wynne Ragland, Jr.*)

*Figure 1-29*
Electronic art output to a pen plotter from software specially designed by the artist to emulate his style. The pen plotter includes multiple pens and painting instruments, including Chinese brushes. (*Courtesy of the Williams Gallery. Copyright © by Roman Verostko, Minneapolis College of Art & Design.*)

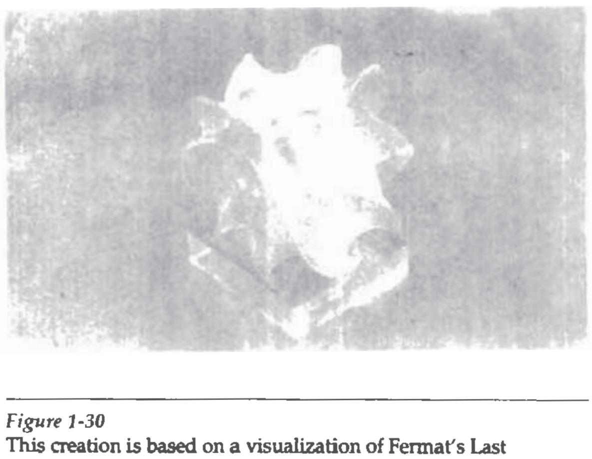


*Figure 1-30*
This creation is based on a visualization of Fermat's Last Theorem, $x^n + y^n = z^n$, with $n = 5$, by Andrew Hanson, Department of Computer Science, Indiana University. The image was rendered using Mathematica and Wavefront software. (*Courtesy of the Williams Gallery. Copyright © 1991 by Stewart Dickson.*)

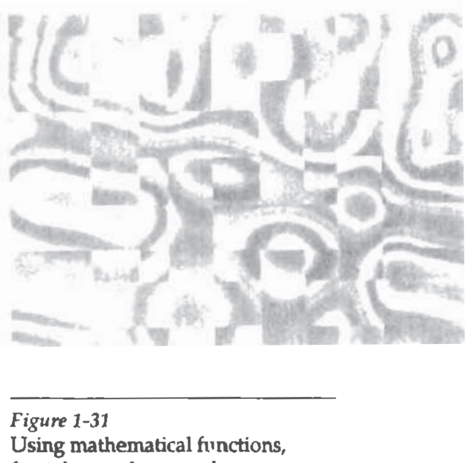


*Figure 1-31*
Using mathematical functions, fractal procedures, and supercomputers, this artist-composer experiments with various designs to synthesize form and color with musical composition. (*Courtesy of Brian Evans, Vanderbilt University.*)

tronic art created with the aid of mathematical relationships is shown in Fig. 1-31. The artwork of this composer is often designed in relation to frequency variations and other parameters in a musical composition to produce a video that integrates visual and aural patterns.

Although we have spent some time discussing current techniques for generating electronic images in the fine arts, these methods are also applied in commercial art for logos and other designs, page layouts combining text and graphics, TV advertising spots, and other areas. A workstation for producing page layouts that combine text and graphics is illustrated in Fig. 1-32.

For many applications of commercial art (and in motion pictures and other applications), photorealistic techniques are used to render images of a product. Figure 1-33 shows an example of logo design, and Fig. 1-34 gives three computer graphics images for product advertising. Animations are also used frequently in advertising, and television commercials are produced frame by frame, where

*Figure 1-32*
Page-layout workstation. (*Courtesy of Visual Technology.*)

*Figure 1-33*
Three-dimensional rendering for a logo. (*Courtesy of Vertigo Technology, Inc.*)

(a) (b)

*Figure 1-34*
Product advertising. (*Courtesy of (a) Audrey Fleisher and (b) and (c) SOFTIMAGE, Inc.*)

each frame of the motion is rendered and saved as an image file. In each successive frame, the motion is simulated by moving object positions slightly from their positions in the previous frame. When all frames in the animation sequence have been rendered, the frames are transferred to film or stored in a video buffer for playback. Film animations require 24 frames for each second in the animation sequence. If the animation is to be played back on a video monitor, 30 frames per second are required.

A common graphics method employed in many commercials is *morphing*, where one object is transformed (metamorphosed) into another. This method has been used in TV commercials to turn an oil can into an automobile engine, an automobile into a tiger, a puddle of water into a tire, and one person's face into another face. An example of morphing is given in Fig. 1-40.

## 1-4 ENTERTAINMENT

Computer graphics methods are now commonly used in making motion pictures, music videos, and television shows. Sometimes the graphics scenes are displayed by themselves, and sometimes graphics objects are combined with the actors and live scenes.

A graphics scene generated for the movie *Star Trek—The Wrath of Khan* is shown in Fig. 1-35. The planet and spaceship are drawn in wireframe form and will be shaded with rendering methods to produce solid surfaces. Figure 1-36 shows scenes generated with advanced modeling and surface-rendering methods for two award-winning short films.

Many TV series regularly employ computer graphics methods. Figure 1-37 shows a scene produced for the series *Deep Space Nine*. And Fig. 1-38 shows a wireframe person combined with actors in a live scene for the series *Stay Tuned*.

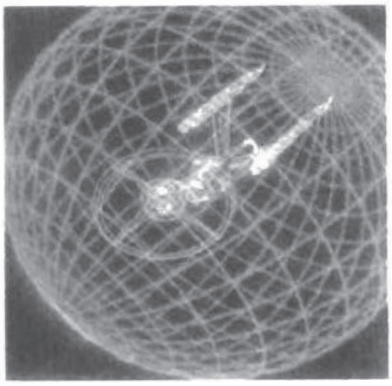


*Figure 1-35*
Graphics developed for the Paramount Pictures movie *Star Trek—The Wrath of Khan*. (*Courtesy of Evans & Sutherland.*)

In Fig. 1-39, we have a highly realistic image taken from a reconstruction of thirteenth-century Dadu (now Beijing) for a Japanese broadcast.

Music videos use graphics in several ways. Graphics objects can be combined with the live action, as in Fig.1-38, or graphics and image processing techniques can be used to produce a transformation of one person or object into another (morphing). An example of morphing is shown in the sequence of scenes in Fig. 1-40, produced for the David Byrne video *She's Mad*.


(a)

(b)

*Figure 1-36*
(a) A computer-generated scene from the film *Red's Dream*, copyright © Pixar 1987. (b) A computer-generated scene from the film *Knickknack*, copyright © Pixar 1989. (*Courtesy of Pixar.*)

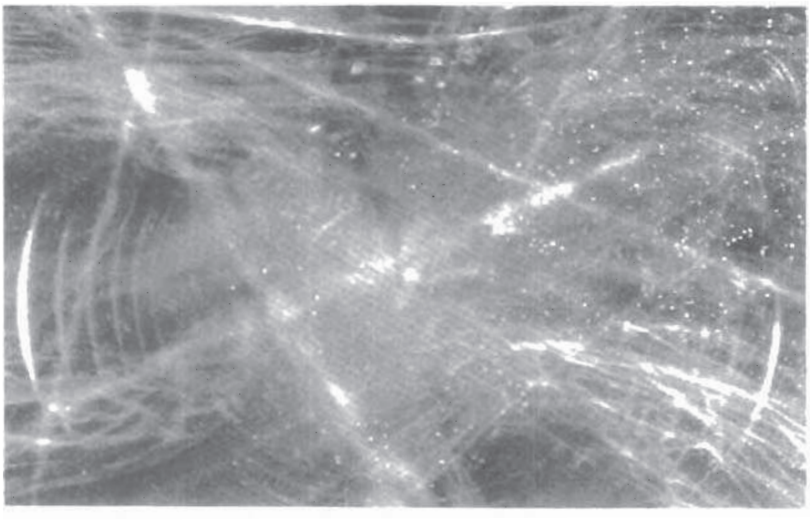


*Figure 1-37*
A graphics scene in the TV series *Deep Space Nine*. (*Courtesy of Rhythm & Hues Studios.*)

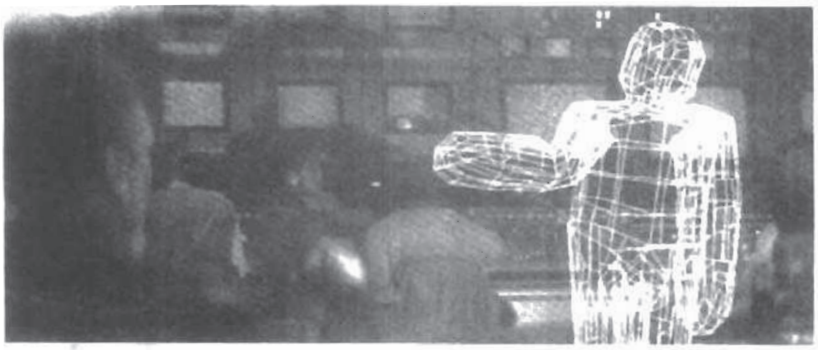


*Figure 1-38*
Graphics combined with a live scene in the TV series *Stay Tuned*. (*Courtesy of Rhythm & Hues Studios.*)

*Figure 1-39*
An image from a reconstruction of thirteenth-century Dadu (Beijing today), created by Taisei Corporation (Tokyo) and rendered with TDI software. (*Courtesy of Thompson Digital Image, Inc.*)

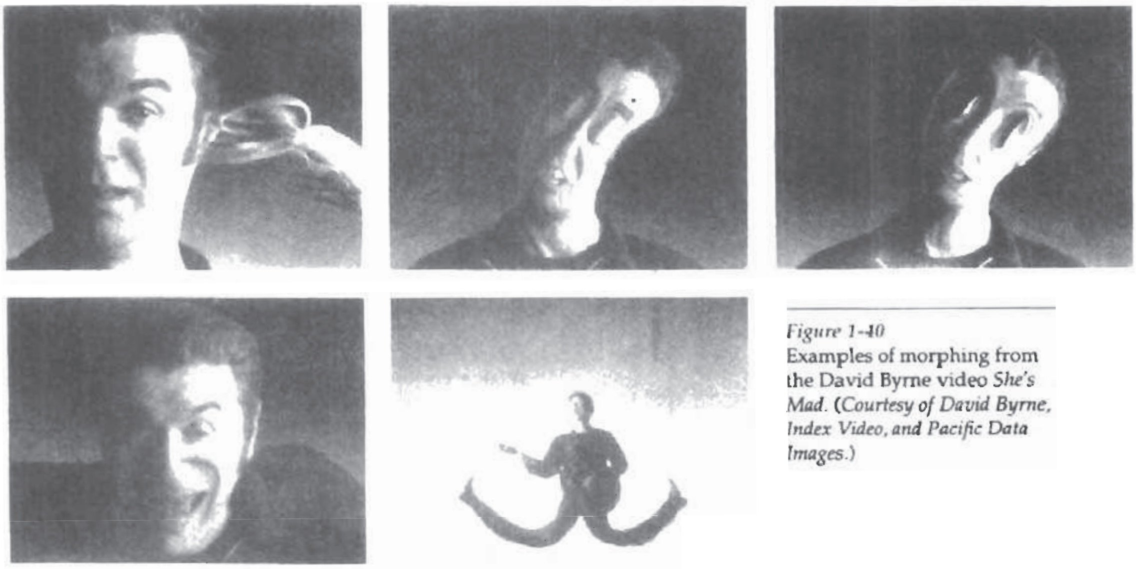


Figure 1-40
Examples of morphing from the David Byrne video *She's Mad*. (*Courtesy of David Byrne, Index Video, and Pacific Data Images.*)

## 1-5 EDUCATION AND TRAINING

Computer-generated models of physical, financial, and economic systems are often used as educational aids. Models of physical systems, physiological systems, population trends, or equipment, such as the color-coded diagram in Fig. 1-41, can help trainees to understand the operation of the system.

For some training applications, special systems are designed. Examples of such specialized systems are the simulators for practice sessions or training of ship captains, aircraft pilots, heavy-equipment operators, and air traffic-control personnel. Some simulators have no video screens; for example, a flight simulator with only a control panel for instrument flying. But most simulators provide graphics screens for visual operation. Two examples of large simulators with internal viewing systems are shown in Figs. 1-42 and 1-43. Another type of viewing system is shown in Fig. 1-44. Here a viewing screen with multiple panels is mounted in front of the simulator, and color projectors display the flight scene on the screen panels. Similar viewing systems are used in simulators for training aircraft control-tower personnel. Figure 1-45 gives an example of the instructor's area in a flight simulator. The keyboard is used to input parameters affecting the airplane performance or the environment, and the pen plotter is used to chart the path of the aircraft during a training session.

Scenes generated for various simulators are shown in Figs. 1-46 through 1-48. An output from an automobile-driving simulator is given in Fig. 1-49. This simulator is used to investigate the behavior of drivers in critical situations. The drivers' reactions are then used as a basis for optimizing vehicle design to maximize traffic safety.

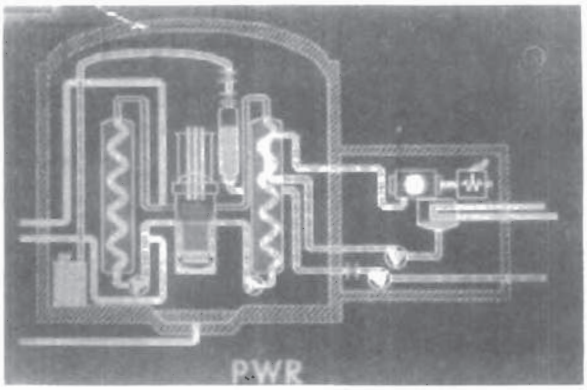



*Figure 1-41*
Color-coded diagram used to explain the operation of a nuclear reactor. (*Courtesy of Los Alamos National Laboratory.*)

*Figure 1-42*
A large, enclosed flight simulator with a full-color visual system and six degrees of freedom in its motion. (*Courtesy of Frasca International.*)

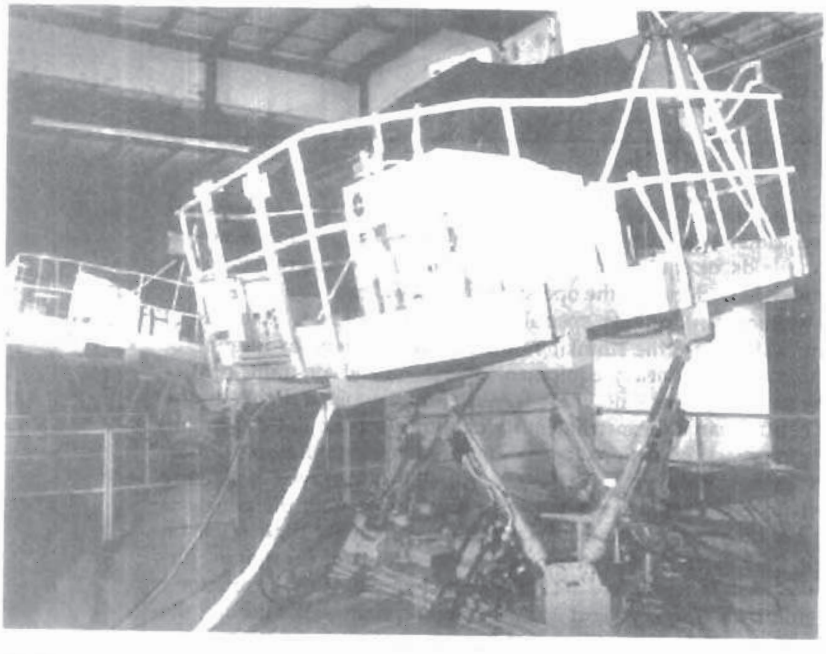


*Figure 1-43*
A military tank simulator with a visual imagery system. (*Courtesy of Mediatech and GE Aerospace.*)

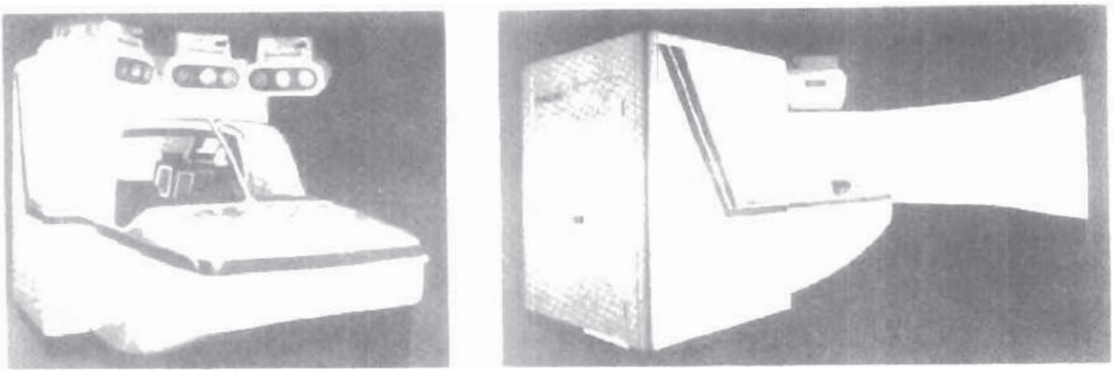


*Figure 1-44*
A flight simulator with an external full-color viewing system. (*Courtesy of Frasca International.*)

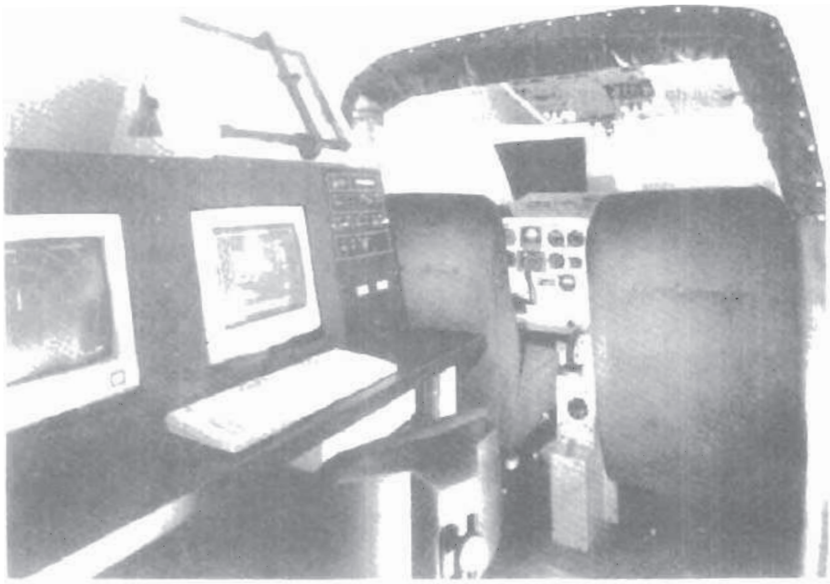


*Figure 1-45*
An instructor's area in a flight simulator. The equipment allows the instructor to monitor flight conditions and to set airplane and environment parameters. (*Courtesy of Frasca International.*)

*Figure 1-46*
Flight-simulator imagery. (*Courtesy of Evans & Sutherland.*)

*Figure 1-47*
Imagery generated for a naval simulator. (*Courtesy of Evans & Sutherland.*)

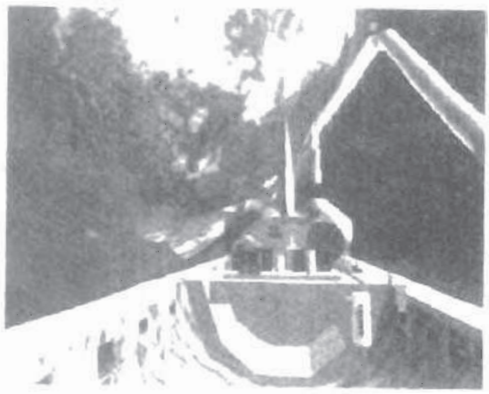


*Figure 1-48*
Space shuttle imagery. (*Courtesy of Mediatech and GE Aerospace.*)

*Figure 1-49*
Imagery from an automobile simulator used to test driver reaction. (*Courtesy of Evans & Sutherland.*)

## 1-6 VISUALIZATION

Scientists, engineers, medical personnel, business analysts, and others often need to analyze large amounts of information or to study the behavior of certain processes. Numerical simulations carried out on supercomputers frequently produce data files containing thousands and even millions of data values. Similarly, satellite cameras and other sources are amassing large data files faster than they can be interpreted. Scanning these large sets of numbers to determine trends and relationships is a tedious and ineffective process. But if the data are converted to a visual form, the trends and patterns are often immediately apparent. Figure 1-50 shows an example of a large data set that has been converted to a color-coded display of relative heights above a ground plane. Once we have plotted the density values in this way, we can see easily the overall pattern of the data. Producing graphical representations for scientific, engineering, and medical data sets and processes is generally referred to as *scientific visualization*. And the term *business visualization* is used in connection with data sets related to commerce, industry, and other nonscientific areas.

There are many different kinds of data sets, and effective visualization schemes depend on the characteristics of the data. A collection of data can contain scalar values, vectors, higher-order tensors, or any combination of these data types. And data sets can be two-dimensional or three-dimensional. Color coding is just one way to visualize a data set. Additional techniques include contour plots, graphs and charts, surface renderings, and visualizations of volume interiors. In addition, image processing techniques are combined with computer graphics to produce many of the data visualizations.

Mathematicians, physical scientists, and others use visual techniques to analyze mathematical functions and processes or simply to produce interesting graphical representations. A color plot of mathematical curve functions is shown in Fig. 1-51, and a surface plot of a function is shown in Fig. 1-52. Fractal proce-

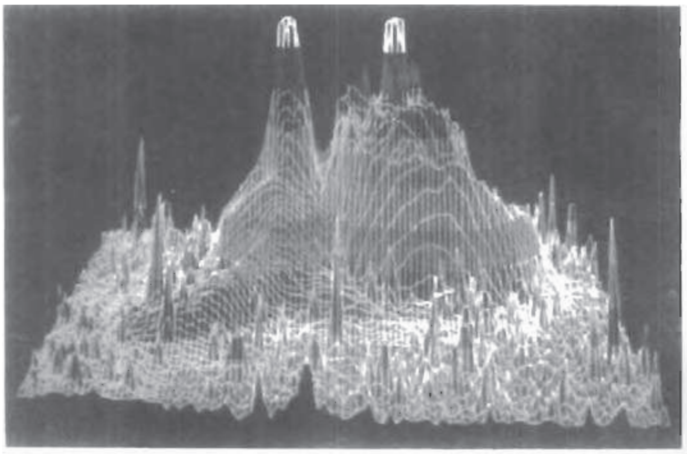


*Figure 1-50*
A color-coded plot with 16 million density points of relative brightness observed for the Whirlpool Nebula reveals two distinct galaxies. (*Courtesy of Los Alamos National Laboratory.*)

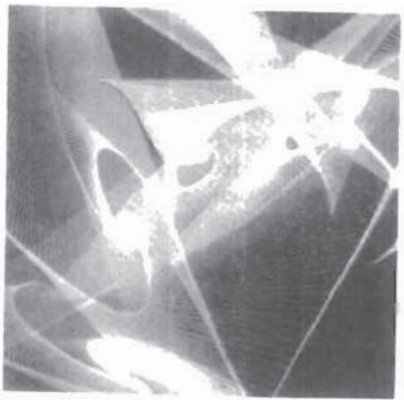


*Figure 1-51*
Mathematical curve functions plotted in various color combinations. (*Courtesy of Melvin L. Prueitt, Los Alamos National Laboratory.*)

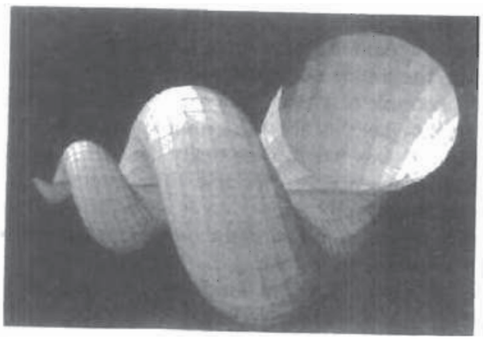


*Figure 1-52*
Lighting effects and surface-rendering techniques were applied to produce this surface representation for a three-dimensional function. (*Courtesy of Wolfram Research, Inc, The Maker of Mathematica.*)

dures using quaternions generated the object shown in Fig. 1-53, and a topological structure is displayed in Fig. 1-54. Scientists are also developing methods for visualizing general classes of data. Figure 1-55 shows a general technique for graphing and modeling data distributed over a spherical surface.

A few of the many other visualization applications are shown in Figs. 1-56 through 1-69. These figures show airflow over the surface of a space shuttle, numerical modeling of thunderstorms, study of crack propagation in metals, a color-coded plot of fluid density over an airfoil, a cross-sectional slicer for data sets, protein modeling, stereoscopic viewing of molecular structure, a model of the ocean floor, a Kuwaiti oil-fire simulation, an air-pollution study, a corn-growing study, reconstruction of Arizona's Chaco Canyon ruins, and a graph of automobile accident statistics.

*Figure 1-53*
A four-dimensional object projected into three-dimensional space, then projected to a video monitor, and color coded. The object was generated using quaternions and fractal squaring procedures, with an octant subtracted to show the complex Julia set. (*Courtesy of John C. Hart, School of Electrical Engineering and Computer Science, Washington State University.*)

*Figure 1-54*
Four views from a real-time, interactive computer-animation study of minimal surfaces ("snails") in the 3-sphere projected to three-dimensional Euclidean space. (*Courtesy of George Francis, Department of Mathematics and the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign. Copyright © 1993.*)

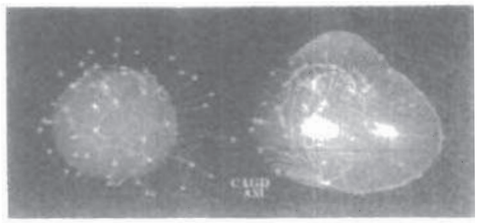


*Figure 1-55*
A method for graphing and modeling data distributed over a spherical surface. (*Courtesy of Greg Nielson, Computer Science Department, Arizona State University.*)

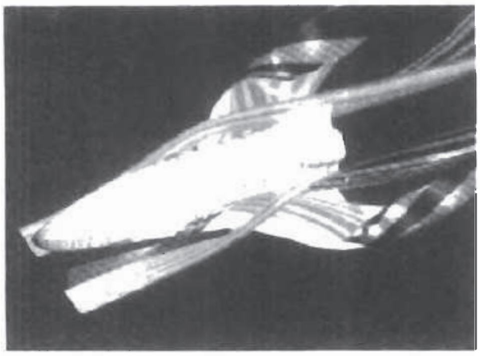


*Figure 1-56*
A visualization of stream surfaces flowing past a space shuttle by Jeff Hultquist and Eric Raible, NASA Ames. (*Courtesy of Sam Uselton, NASA Ames Research Center.*)

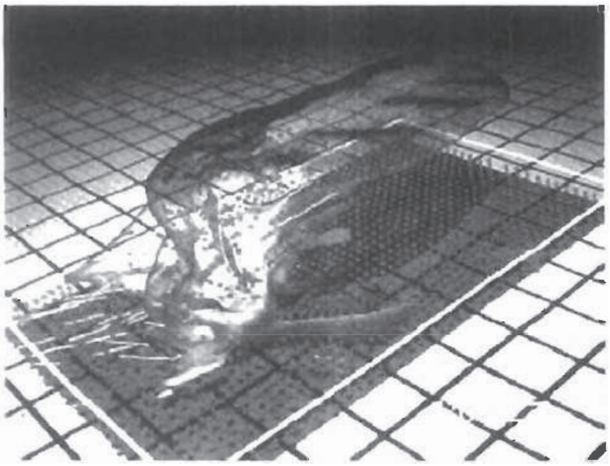


*Figure 1-57*
Numerical model of airflow inside a thunderstorm. (*Courtesy of Bob Wilhelmson, Department of Atmospheric Sciences and the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.*)

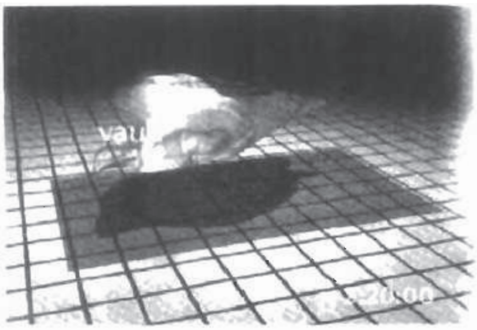


*Figure 1-58*
Numerical model of the surface of a thunderstorm. (*Courtesy of Bob Wilhelmson, Department of Atmospheric Sciences and the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.*)

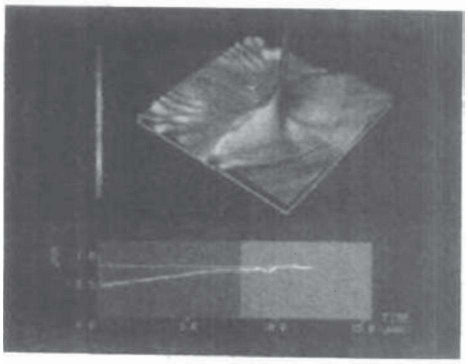


*Figure 1-59*
Color-coded visualization of stress energy density in a crack-propagation study for metal plates, modeled by Bob Haber. *(Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.)*

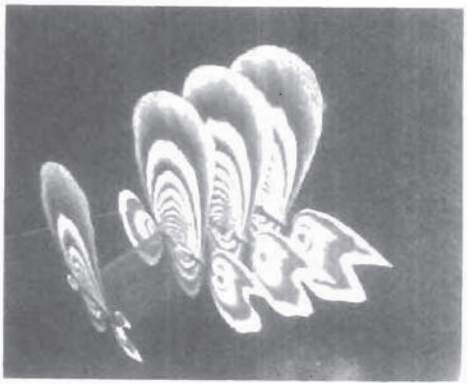


*Figure 1-60*
A fluid dynamic simulation, showing a color-coded plot of fluid density over a span of grid planes around an aircraft wing, developed by Lee-Hian Quek, John Eickemeyer, and Jeffery Tan. *(Courtesy of the Information Technology Institute, Republic of Singapore.)*

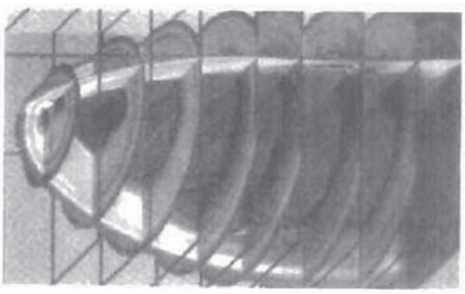


*Figure 1-61*
Commercial slicer-dicer software, showing color-coded data values over cross-sectional slices of a data set. *(Courtesy of Spyglass, Inc.)*

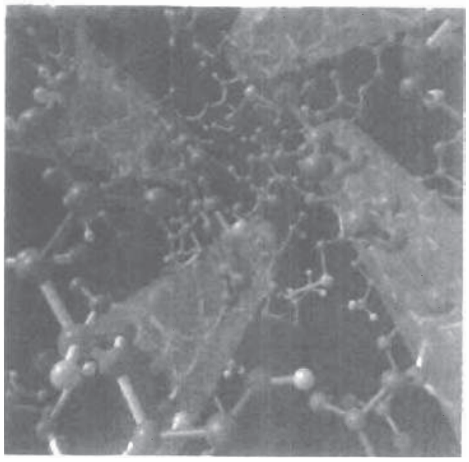


*Figure 1-62*
Visualization of a protein structure by Jay Siegel and Kim Baldridge, SDSC. *(Courtesy of Stephanie Sides, San Diego Supercomputer Center.)*

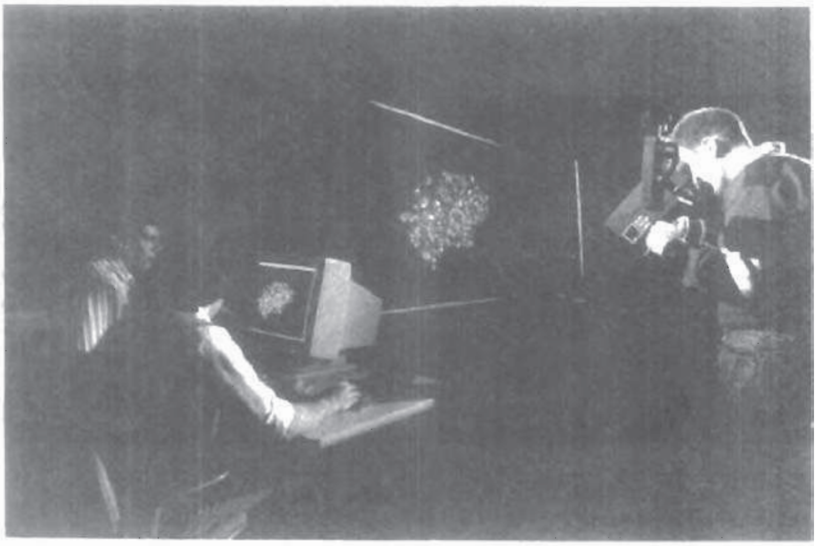


*Figure 1-63*
Stereoscopic viewing of a molecular structure using a "boom" device. *(Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.)*

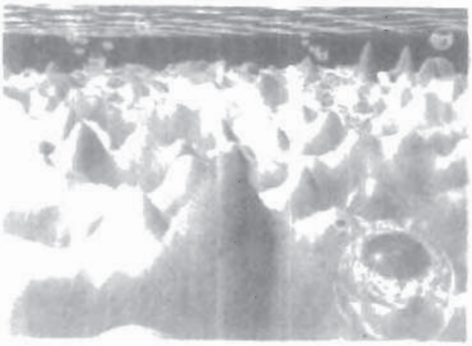


**Figure 1-64**
**One image from a stereoscopic pair, showing a visualization of the ocean floor obtained from satellite data, by David Sandwell and Chris Small, Scripps Institution of Oceanography, and Jim Mcleod, SDSC.** *(Courtesy of Stephanie Sides, San Diego Supercomputer Center.)*

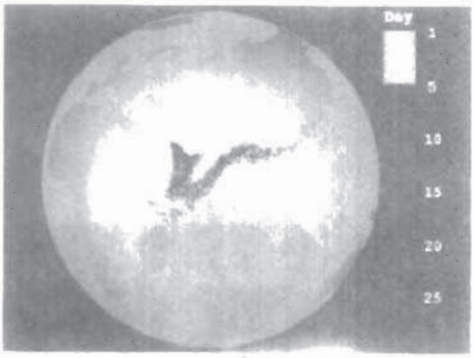



**Figure 1-65**
**A simulation of the effects of the Kuwaiti oil fire, by Gary Glatzmeier, Chuck Hanson, and Paul Hinker.** *(Courtesy of Mike Krogh, Advanced Computing Laboratory at Los Alamos National Laboratory.)*

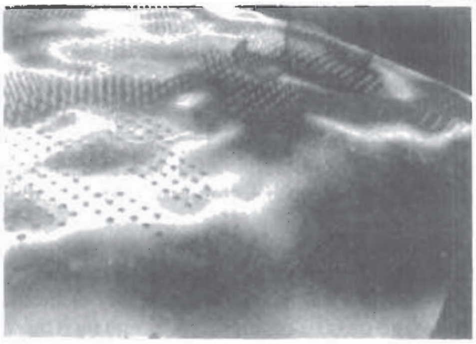


*Figure 1-66*
A visualization of pollution over the earth's surface by Tom Palmer, Cray Research Inc./NCSC; Chris Landreth, NCSC; and Dave Bock, NCSC. Pollutant $SO_4$ is plotted as a blue surface, acid-rain deposition is a color plane on the map surface, and rain concentration is shown as clear cylinders. (*Courtesy of the North Carolina Supercomputing Center/MCNC.*)

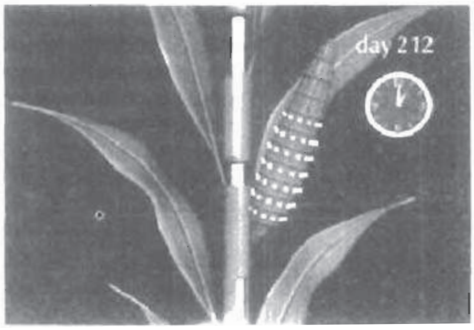



*Figure 1-67*
One frame of an animation sequence showing the development of a corn ear. (*Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.*)

*Figure 1-68*
A visualization of the reconstruction of the ruins at Chaco Canyon, Arizona. (*Courtesy of Melvin L. Prueitt, Los Alamos National Laboratory. Data supplied by Stephen H. Lekson.*)

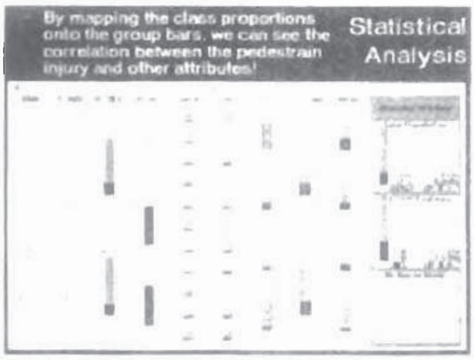



*Figure 1-69*
A prototype technique, called *WinViz*, for visualizing tabular multidimensional data is used here to correlate statistical information on pedestrians involved in automobile accidents, developed by a visualization team at ITT. (*Courtesy of Lee-Hian Quek, Information Technology Institute. Republic of Singapore.*)

## 1-7
## IMAGE PROCESSING

Although methods used in computer graphics and image processing overlap, the two areas are concerned with fundamentally different operations. In computer graphics, a computer is used to create a picture. **Image processing**, on the other hand, applies techniques to modify or interpret existing pictures, such as photographs and TV scans. Two principal applications of image processing are (1) improving picture quality and (2) machine perception of visual information, as used in robotics.

To apply image-processing methods, we first digitize a photograph or other picture into an image file. Then digital methods can be applied to rearrange picture parts, to enhance color separations, or to improve the quality of shading. An example of the application of image-processing methods to enhance the quality of a picture is shown in Fig. 1-70. These techniques are used extensively in commercial art applications that involve the retouching and rearranging of sections of photographs and other artwork. Similar methods are used to analyze satellite photos of the earth and photos of galaxies.

Medical applications also make extensive use of image-processing techniques for picture enhancements, in tomography and in simulations of operations. Tomography is a technique of X-ray photography that allows cross-sectional views of physiological systems to be displayed. Both *computed X-ray tomography* (CT) and *position emission tomography* (PET) use projection methods to reconstruct cross sections from digital data. These techniques are also used to

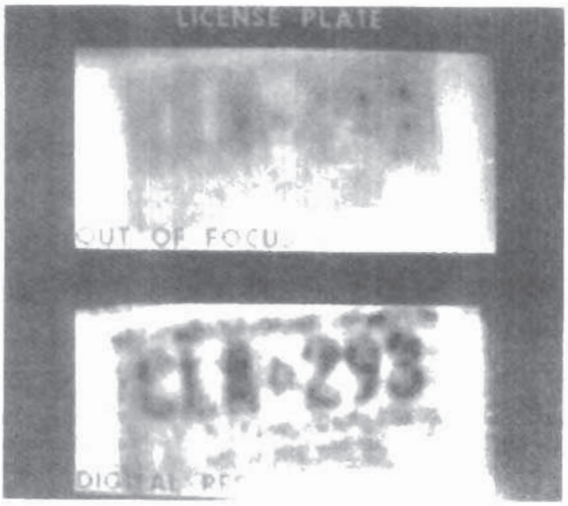



*Figure 1-70*
A blurred photograph of a license plate becomes legible after the application of image-processing techniques. (*Courtesy of Los Alamos National Laboratory.*)

monitor internal functions and show cross sections during surgery. Other medical imaging techniques include ultrasonics and nuclear medicine scanners. With ultrasonics, high-frequency sound waves, instead of X-rays, are used to generate digital data. Nuclear medicine scanners collect digital data from radiation emitted from ingested radionuclides and plot color-coded images.

Image processing and computer graphics are typically combined in many applications. Medicine, for example, uses these techniques to model and study physical functions, to design artificial limbs, and to plan and practice surgery. The last application is generally referred to as *computer-aided surgery*. Two-dimensional cross sections of the body are obtained using imaging techniques. Then the slices are viewed and manipulated using graphics methods to simulate actual surgical procedures and to try out different surgical cuts. Examples of these medical applications are shown in Figs. 1-71 and 1-72.

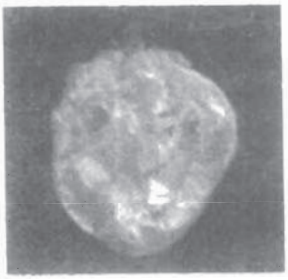


*Figure 1-71*
One frame from a computer animation visualizing cardiac activation levels within regions of a semitransparent volume-rendered dog heart. Medical data provided by William Smith, Ed Simpson, and G. Allan Johnson, Duke University. Image-rendering software by Tom Palmer, Cray Research, Inc./NCSC. (*Courtesy of Dave Bock, North Carolina Supercomputing Center/MCNC.*)

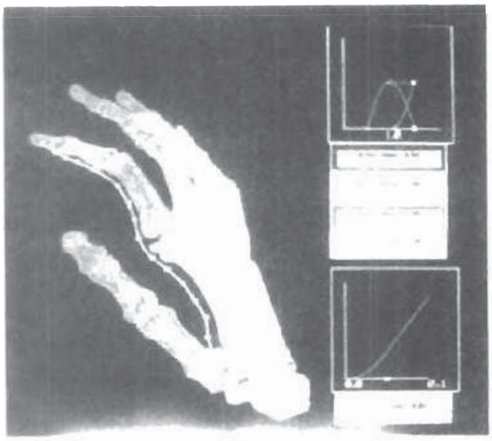


*Figure 1-72*
One image from a stereoscopic pair showing the bones of a human hand. The images were rendered by Inmo Yoon, D. E. Thompson, and W. N. Waggenspack, Jr., LSU, from a data set obtained with CT scans by Rehabilitation Research, GWLNHDC. These images show a possible tendon path for reconstructive surgery. (*Courtesy of IMRLAB, Mechanical Engineering, Louisiana State University.*)

## 1-8 GRAPHICAL USER INTERFACES

It is common now for software packages to provide a **graphical interface**. A major component of a graphical interface is a window manager that allows a user to display multiple-window areas. Each window can contain a different process that can contain graphical or nongraphical displays. To make a particular window active, we simply click in that window using an interactive pointing device.

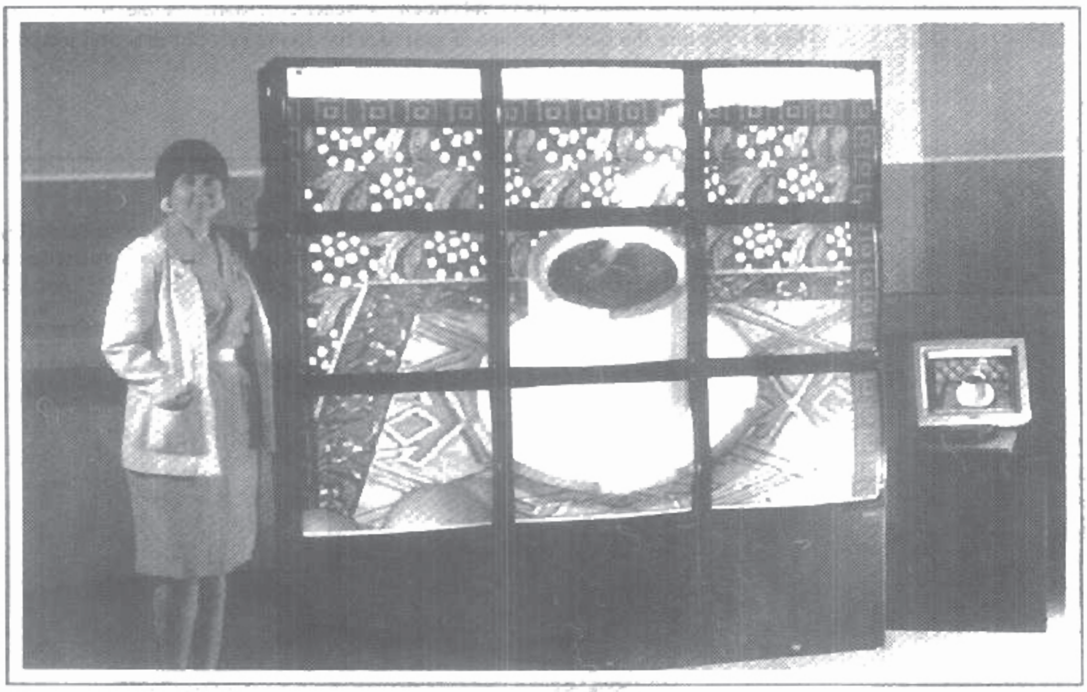
Interfaces also display menus and icons for fast selection of processing options or parameter values. An **icon** is a graphical symbol that is designed to look like the processing option it represents. The advantages of icons are that they take up less screen space than corresponding textual descriptions and they can be understood more quickly if well designed. Menus contain lists of textual descriptions and icons.

Figure 1-73 illustrates a typical graphical interface, containing a window manager, menu displays, and icons. In this example, the menus allow selection of processing options, color values, and graphics parameters. The icons represent options for painting, drawing, zooming, typing text strings, and other operations connected with picture construction.


***Figure 1-73***
**A graphical user interface, showing multiple window areas, menus, and icons. (*Courtesy of Image-In Corporation.*)**

CHAPTER

# 2 Overview of Graphics Systems



Due to the widespread recognition of the power and utility of computer graphics in virtually all fields, a broad range of graphics hardware and software systems is now available. Graphics capabilities for both two-dimensional and three-dimensional applications are now common on general-purpose computers, including many hand-held calculators. With personal computers, we can use a wide variety of interactive input devices and graphics software packages. For higher-quality applications, we can choose from a number of sophisticated special-purpose graphics hardware systems and technologies. In this chapter, we explore the basic features of graphics hardware components and graphics software packages.

## 2-1 VIDEO DISPLAY DEVICES

Typically, the primary output device in a graphics system is a video monitor (Fig. 2-1). The operation of most video monitors is based on the standard **cathode-ray tube (CRT)** design, but several other technologies exist and solid-state monitors may eventually predominate.

*Figure 2-1*
A computer graphics workstation. *(Courtesy of Tektronix, Inc.)*

## Refresh Cathode-Ray Tubes



Figure 2-2 illustrates the basic operation of a CRT. A beam of electrons (*cathode rays*), emitted by an electron gun, passes through focusing and deflection systems that direct the beam toward specified positions on the phosphor-coated screen. The phosphor then emits a small spot of light at each position contacted by the electron beam. Because the light emitted by the phosphor fades very rapidly, some method is needed for maintaining the screen picture. One way to keep the phosphor glowing is to redraw the picture repeatedly by quickly directing the electron beam back over the same points. This type of display is called a **refresh CRT**.

The primary components of an electron gun in a CRT are the heated metal cathode and a control grid (Fig. 2-3). Heat is supplied to the cathode by directing a current through a coil of wire, called the filament, inside the cylindrical cathode structure. This causes electrons to be "boiled off" the hot cathode surface. In the vacuum inside the CRT envelope, the free, negatively charged electrons are then accelerated toward the phosphor coating by a high positive voltage. The acceler-

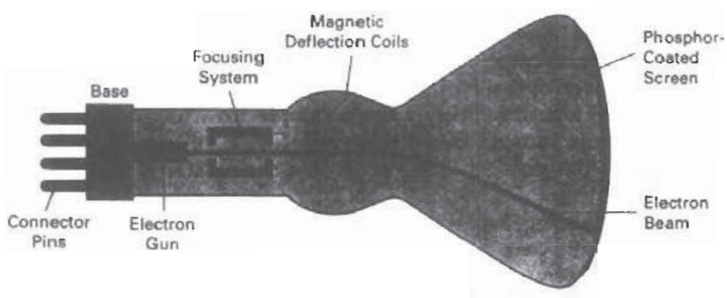



*Figure 2-2*
Basic design of a magnetic-deflection CRT.

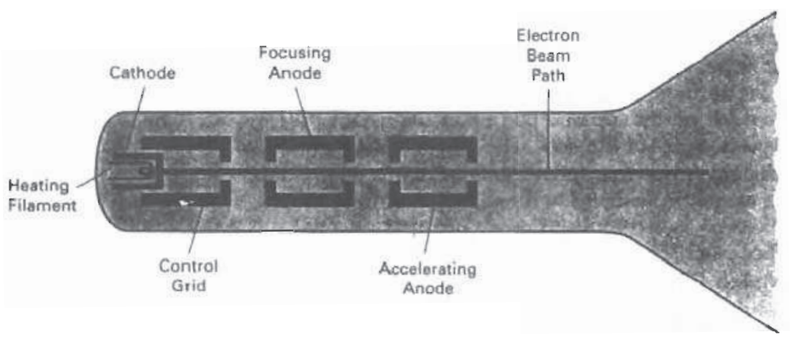



*Figure 2-3*
Operation of an electron gun with an accelerating anode.

ating voltage can be generated with a positively charged metal coating on the inside of the CRT envelope near the phosphor screen, or an accelerating anode can be used, as in Fig. 2-3. Sometimes the electron gun is built to contain the accelerating anode and focusing system within the same unit.

Intensity of the electron beam is controlled by setting voltage levels on the control grid, which is a metal cylinder that fits over the cathode. A high negative voltage applied to the control grid will shut off the beam by repelling electrons and stopping them from passing through the small hole at the end of the control grid structure. A smaller negative voltage on the control grid simply decreases the number of electrons passing through. Since the amount of light emitted by the phosphor coating depends on the number of electrons striking the screen, we control the brightness of a display by varying the voltage on the control grid. We specify the intensity level for individual screen positions with graphics software commands, as discussed in Chapter 3.

The focusing system in a CRT is needed to force the electron beam to converge into a small spot as it strikes the phosphor. Otherwise, the electrons would repel each other, and the beam would spread out as it approaches the screen. Focusing is accomplished with either electric or magnetic fields. Electrostatic focusing is commonly used in television and computer graphics monitors. With electrostatic focusing, the electron beam passes through a positively charged metal cylinder that forms an electrostatic lens, as shown in Fig. 2-3. The action of the electrostatic lens focuses the electron beam at the center of the screen, in exactly the same way that an optical lens focuses a beam of light at a particular focal distance. Similar lens focusing effects can be accomplished with a magnetic field set up by a coil mounted around the outside of the CRT envelope. Magnetic lens focusing produces the smallest spot size on the screen and is used in special-purpose devices.

Additional focusing hardware is used in high-precision systems to keep the beam in focus at all screen positions. The distance that the electron beam must travel to different points on the screen varies because the radius of curvature for most CRTs is greater than the distance from the focusing system to the screen center. Therefore, the electron beam will be focused properly only at the center of the screen. As the beam moves to the outer edges of the screen, displayed images become blurred. To compensate for this, the system can adjust the focusing according to the screen position of the beam.

As with focusing, deflection of the electron beam can be controlled either with electric fields or with magnetic fields. Cathode-ray tubes are now commonly constructed with magnetic deflection coils mounted on the outside of the CRT envelope, as illustrated in Fig. 2-2. Two pairs of coils are used, with the coils in each pair mounted on opposite sides of the neck of the CRT envelope. One pair is mounted on the top and bottom of the neck, and the other pair is mounted on opposite sides of the neck. The magnetic field produced by each pair of coils results in a transverse deflection force that is perpendicular both to the direction of the magnetic field and to the direction of travel of the electron beam. Horizontal deflection is accomplished with one pair of coils, and vertical deflection by the other pair. The proper deflection amounts are attained by adjusting the current through the coils. When electrostatic deflection is used, two pairs of parallel plates are mounted inside the CRT envelope. One pair of plates is mounted horizontally to control the vertical deflection, and the other pair is mounted vertically to control horizontal deflection (Fig. 2-4).

Spots of light are produced on the screen by the transfer of the CRT beam energy to the phosphor. When the electrons in the beam collide with the phos-

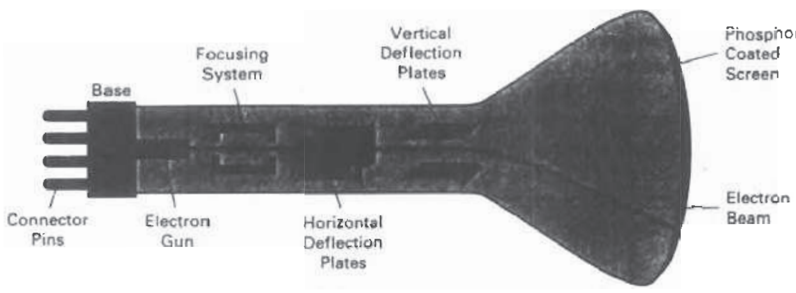



*Figure 2-4*
Electrostatic deflection of the electron beam in a CRT.

phor coating, they are stopped and their kinetic energy is absorbed by the phosphor. Part of the beam energy is converted by friction into heat energy, and the remainder causes electrons in the phosphor atoms to move up to higher quantum-energy levels. After a short time, the "excited" phosphor electrons begin dropping back to their stable ground state, giving up their extra energy as small quantums of light energy. What we see on the screen is the combined effect of all the electron light emissions: a glowing spot that quickly fades after all the excited phosphor electrons have returned to their ground energy level. The frequency (or color) of the light emitted by the phosphor is proportional to the energy difference between the excited quantum state and the ground state.

Different kinds of phosphors are available for use in a CRT. Besides color, a major difference between phosphors is their **persistence**: how long they continue to emit light (that is, have excited electrons returning to the ground state) after the CRT beam is removed. Persistence is defined as the time it takes the emitted light from the screen to decay to one-tenth of its original intensity. Lower-persistence phosphors require higher refresh rates to maintain a picture on the screen without flicker. A phosphor with low persistence is useful for animation; a high-persistence phosphor is useful for displaying highly complex, static pictures. Although some phosphors have a persistence greater than 1 second, graphics monitors are usually constructed with a persistence in the range from 10 to 60 microseconds.

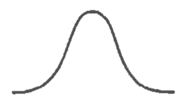


*Figure 2-5*
Intensity distribution of an illuminated phosphor spot on a CRT screen.

Figure 2-5 shows the intensity distribution of a spot on the screen. The intensity is greatest at the center of the spot, and decreases with a Gaussian distribution out to the edges of the spot. This distribution corresponds to the cross-sectional electron density distribution of the CRT beam.

The maximum number of points that can be displayed without overlap on a CRT is referred to as the **resolution**. A more precise definition of resolution is the number of points per centimeter that can be plotted horizontally and vertically, although it is often simply stated as the total number of points in each direction. Spot intensity has a Gaussian distribution (Fig. 2-5), so two adjacent spots will appear distinct as long as their separation is greater than the diameter at which each spot has an intensity of about 60 percent of that at the center of the spot. This overlap position is illustrated in Fig. 2-6. Spot size also depends on intensity. As more electrons are accelerated toward the phospher per second, the CRT beam diameter and the illuminated spot increase. In addition, the increased excitation energy tends to spread to neighboring phosphor atoms not directly in the

*Figure 2-6*
Two illuminated phosphor spots are distinguishable when their separation is greater than the diameter at which a spot intensity has fallen to 60 percent of maximum.

path of the beam, which further increases the spot diameter. Thus, resolution of a CRT is dependent on the type of phosphor, the intensity to be displayed, and the focusing and deflection systems. Typical resolution on high-quality systems is 1280 by 1024, with higher resolutions available on many systems. High-resolution systems are often referred to as *high-definition systems*. The physical size of a graphics monitor is given as the length of the screen diagonal, with sizes varying from about 12 inches to 27 inches or more. A CRT monitor can be attached to a variety of computer systems, so the number of screen points that can actually be plotted depends on the capabilities of the system to which it is attached.

Another property of video monitors is **aspect ratio**. This number gives the ratio of vertical points to horizontal points necessary to produce equal-length lines in both directions on the screen. (Sometimes aspect ratio is stated in terms of the ratio of horizontal to vertical points.) An aspect ratio of 3/4 means that a vertical line plotted with three points has the same length as a horizontal line plotted with four points.

## Raster-Scan Displays

The most common type of graphics monitor employing a CRT is the **raster-scan display**, based on television technology. In a raster-scan system, the electron beam is swept across the screen, one row at a time from top to bottom. As the electron beam moves across each row, the beam intensity is turned on and off to create a pattern of illuminated spots. Picture definition is stored in a memory area called the **refresh buffer** or **frame buffer**. This memory area holds the set of intensity values for all the screen points. Stored intensity values are then retrieved from the refresh buffer and "painted" on the screen one row (**scan line**) at a time (Fig. 2-7). Each screen point is referred to as a **pixel** or **pel** (shortened forms of **picture element**). The capability of a raster-scan system to store intensity information for each screen point makes it well suited for the realistic display of scenes containing subtle shading and color patterns. Home television sets and printers are examples of other systems using raster-scan methods.

Intensity range for pixel positions depends on the capability of the raster system. In a simple black-and-white system, each screen point is either on or off, so only one bit per pixel is needed to control the intensity of screen positions. For a bilevel system, a bit value of 1 indicates that the electron beam is to be turned on at that position, and a value of 0 indicates that the beam intensity is to be off. Additional bits are needed when color and intensity variations can be displayed. Up to 24 bits per pixel are included in high-quality systems, which can require several megabytes of storage for the frame buffer, depending on the resolution of the system. A system with 24 bits per pixel and a screen resolution of 1024 by 1024 requires 3 megabytes of storage for the frame buffer. On a black-and-white system with one bit per pixel, the frame buffer is commonly called a **bitmap**. For systems with multiple bits per pixel, the frame buffer is often referred to as a **pixmap**.

Refreshing on raster-scan displays is carried out at the rate of 60 to 80 frames per second, although some systems are designed for higher refresh rates. Sometimes, refresh rates are described in units of cycles per second, or Hertz (Hz), where a cycle corresponds to one frame. Using these units, we would describe a refresh rate of 60 frames per second as simply 60 Hz. At the end of each scan line, the electron beam returns to the left side of the screen to begin displaying the next scan line. The return to the left of the screen, after refreshing each

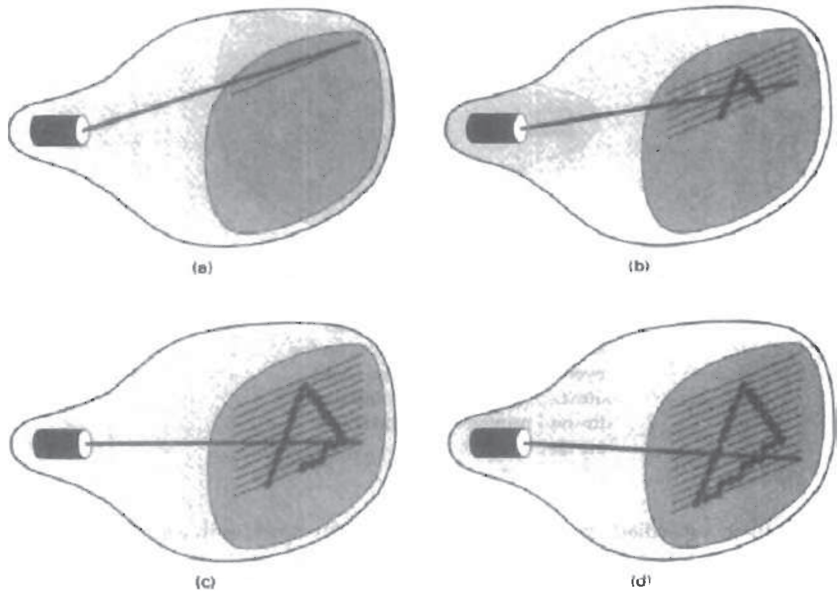



*Figure 2-7*
A raster-scan system displays an object as a set of discrete points across each scan line.

scan line, is called the **horizontal retrace** of the electron beam. And at the end of each frame (displayed in 1/80th to 1/60th of a second), the electron beam returns (**vertical retrace**) to the top left corner of the screen to begin the next frame.

On some raster-scan systems (and in TV sets), each frame is displayed in two passes using an *interlaced* refresh procedure. In the first pass, the beam sweeps across every other scan line from top to bottom. Then after the vertical retrace, the beam sweeps out the remaining scan lines (Fig. 2-8). Interlacing of the scan lines in this way allows us to see the entire screen displayed in one-half the time it would have taken to sweep across all the lines at once from top to bottom. Interlacing is primarily used with slower refreshing rates. On an older, 30 frame-per-second, noninterlaced display, for instance, some flicker is noticeable. But with interlacing, each of the two passes can be accomplished in 1/60th of a second, which brings the refresh rate nearer to 60 frames per second. This is an effective technique for avoiding flicker, providing that adjacent scan lines contain similar display information.

## Random-Scan Displays

When operated as a **random-scan** display unit, a CRT has the electron beam directed only to the parts of the screen where a picture is to be drawn. Random-scan monitors draw a picture one line at a time and for this reason are also referred to as **vector** displays (or **stroke-writing** or **calligraphic** displays). The component lines of a picture can be drawn and refreshed by a random-scan sys-

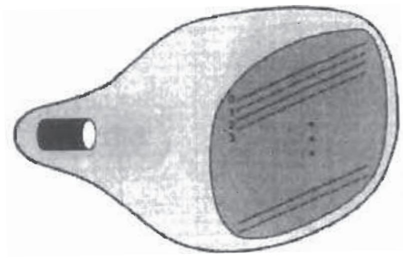


*Figure 2-8*
Interlacing scan lines on a raster-scan display. First, all points on the even-numbered (solid) scan lines are displayed; then all points along the odd-numbered (dashed) lines are displayed.

tem in any specified order (Fig. 2-9). A pen plotter operates in a similar way and is an example of a random-scan, hard-copy device.

Refresh rate on a random-scan system depends on the number of lines to be displayed. Picture definition is now stored as a set of line-drawing commands in an area of memory referred to as the **refresh display file**. Sometimes the refresh display file is called the **display list, display program**, or simply the **refresh buffer**. To display a specified picture, the system cycles through the set of commands in the display file, drawing each component line in turn. After all line-drawing commands have been processed, the system cycles back to the first line command in the list. Random-scan displays are designed to draw all the component lines of a picture 30 to 60 times each second. High-quality vector systems are capable of handling approximately 100,000 "short" lines at this refresh rate. When a small set of lines is to be displayed, each refresh cycle is delayed to avoid refresh rates greater than 60 frames per second. Otherwise, faster refreshing of the set of lines could burn out the phosphor.

Random-scan systems are designed for line-drawing applications and cannot display realistic shaded scenes. Since picture definition is stored as a set of line-drawing instructions and not as a set of intensity values for all screen points, vector displays generally have higher resolution than raster systems. Also, vector displays produce smooth line drawings because the CRT beam directly follows the line path. A raster system, in contrast, produces jagged lines that are plotted as discrete point sets.

## Color CRT Monitors

A CRT monitor displays color pictures by using a combination of phosphors that emit different-colored light. By combining the emitted light from the different phosphors, a range of colors can be generated. The two basic techniques for producing color displays with a CRT are the beam-penetration method and the shadow-mask method.

The **beam-penetration** method for displaying color pictures has been used with random-scan monitors. Two layers of phosphor, usually red and green, are

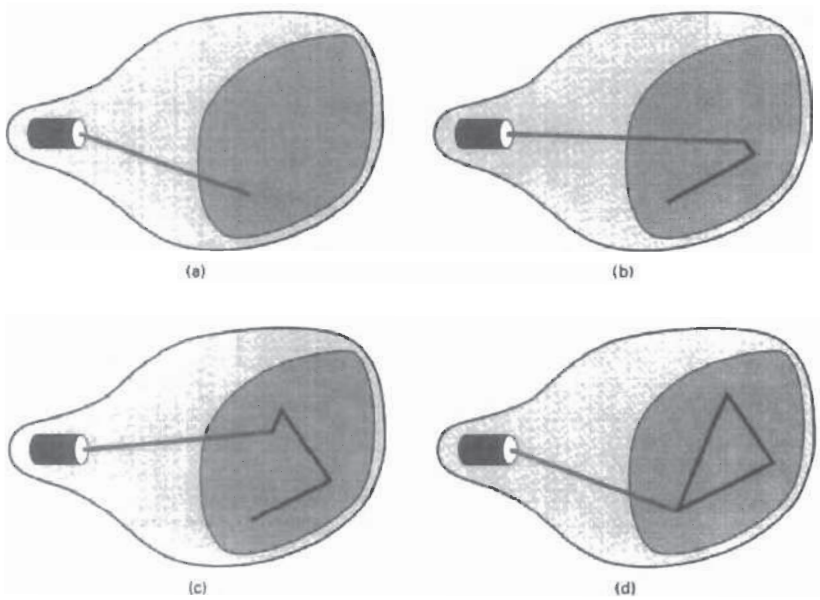



*Figure 2-9*
A random-scan system draws the component lines of an object in any order specified.

coated onto the inside of the CRT screen, and the displayed color depends on how far the electron beam penetrates into the phosphor layers. A beam of slow electrons excites only the outer red layer. A beam of very fast electrons penetrates through the red layer and excites the inner green layer. At intermediate beam speeds, combinations of red and green light are emitted to show two additional colors, orange and yellow. The speed of the electrons, and hence the screen color at any point, is controlled by the beam-acceleration voltage. Beam penetration has been an inexpensive way to produce color in random-scan monitors, but only four colors are possible, and the quality of pictures is not as good as with other methods.

**Shadow-mask** methods are commonly used in raster-scan systems (including color TV) because they produce a much wider range of colors than the beam-penetration method. A shadow-mask CRT has three phosphor color dots at each pixel position. One phosphor dot emits a red light, another emits a green light, and the third emits a blue light. This type of CRT has three electron guns, one for each color dot, and a shadow-mask grid just behind the phosphor-coated screen. Figure 2-10 illustrates the *delta-delta* shadow-mask method, commonly used in color CRT systems. The three electron beams are deflected and focused as a group onto the shadow mask, which contains a series of holes aligned with the phosphor-dot patterns. When the three beams pass through a hole in the shadow mask, they activate a dot triangle, which appears as a small color spot on the screen. The phosphor dots in the triangles are arranged so that each electron beam can activate only its corresponding color dot when it passes through the

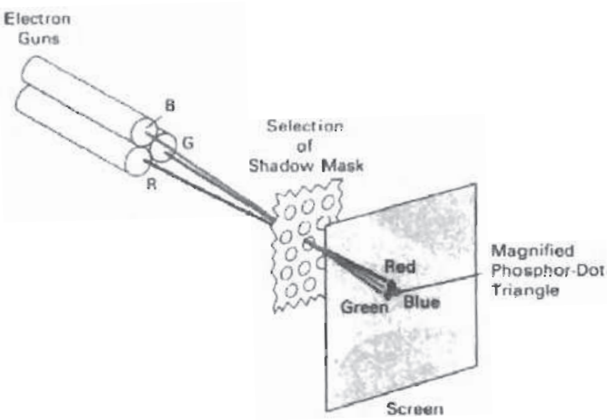



*Figure 2-10*
Operation of a delta-delta, shadow-mask CRT. Three electron guns, aligned with the triangular color-dot patterns on the screen, are directed to each dot triangle by a shadow mask.

shadow mask. Another configuration for the three electron guns is an *in-line* arrangement in which the three electron guns, and the corresponding red–green–blue color dots on the screen, are aligned along one scan line instead of in a triangular pattern. This in-line arrangement of electron guns is easier to keep in alignment and is commonly used in high-resolution color CRTs.

We obtain color variations in a shadow-mask CRT by varying the intensity levels of the three electron beams. By turning off the red and green guns, we get only the color coming from the blue phosphor. Other combinations of beam intensities produce a small light spot for each pixel position, since our eyes tend to merge the three colors into one composite. The color we see depends on the amount of excitation of the red, green, and blue phosphors. A white (or gray) area is the result of activating all three dots with equal intensity. Yellow is produced with the green and red dots only, magenta is produced with the blue and red dots, and cyan shows up when blue and green are activated equally. In some low-cost systems, the electron beam can only be set to on or off, limiting displays to eight colors. More sophisticated systems can set intermediate intensity levels for the electron beams, allowing several million different colors to be generated.

Color graphics systems can be designed to be used with several types of CRT display devices. Some inexpensive home-computer systems and video games are designed for use with a color TV set and an RF (radio-frequency) modulator. The purpose of the RF modulator is to simulate the signal from a broadcast TV station. This means that the color and intensity information of the picture must be combined and superimposed on the broadcast-frequency carrier signal that the TV needs to have as input. Then the circuitry in the TV takes this signal from the RF modulator, extracts the picture information, and paints it on the screen. As we might expect, this extra handling of the picture information by the RF modulator and TV circuitry decreases the quality of displayed images.

**Composite monitors** are adaptations of TV sets that allow bypass of the broadcast circuitry. These display devices still require that the picture informa-